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Switched Flip-Flop based Preprocessing Circuit for ISFETs

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Abstract: In this paper, a preprocessing circuit for ISFETs (Ion-sensitive field-effect transistors) to measure hydrogen-ion concentration in electrolyte is presented. A modified flip-flop is the main part of the circuit. The modification consists in replacing the standard transistors by ISFETs and periodically switching the supply voltage on and off. Concentration of hydrogen ions to be measured discontinues the flip-flop value symmetry, which means that by switching the supply voltage on the flip-flop goes to one of two stable states, 'one' or 'zero'. The recovery of the value symmetry can be achieved by changing a balanced voltage, which is incorporated to the flip-flop, to bring the flip-flop to a 50% position (probability of 'one' equals to probability of 'zero'). Thus, the balanced voltage reflects the measured concentration of hydrogen ions. Its magnitude is set automatically by using a feedback circuit whose input is connected to the flip-flop output. The preprocessing circuit, as the whole, is the well-known Δ modulator in which the switched flip-flop serves as a comparator and a sampling circuit. The advantages of this approach in comparison to those of standard approaches are discussed. Finally, theoretical results are verified by simulations with TSPICE and a good agreement is reported.

Keywords: ISFET, pH sensitivity, switched flip-flop.

Introduction

Essentially, the ISFET is a Metal-Oxide-Semiconductor FET (MOSFET) in which the standard metal-polysilicon gate is replaced by a more complex structure sensitive to the hydrogen-ion concentration. The gate structure, presented in Fig. 1, consists of a reference electrode and an insulating material between which a measured electrolyte flows. The electrolyte closes the electric gate-source circuit and the ion concentration influences the gate potential, which in turns modifies the transistor's threshold voltage. In such a way, the hydrogen-ion concentration can exercise an electrostatic control on the drain-source current [1].

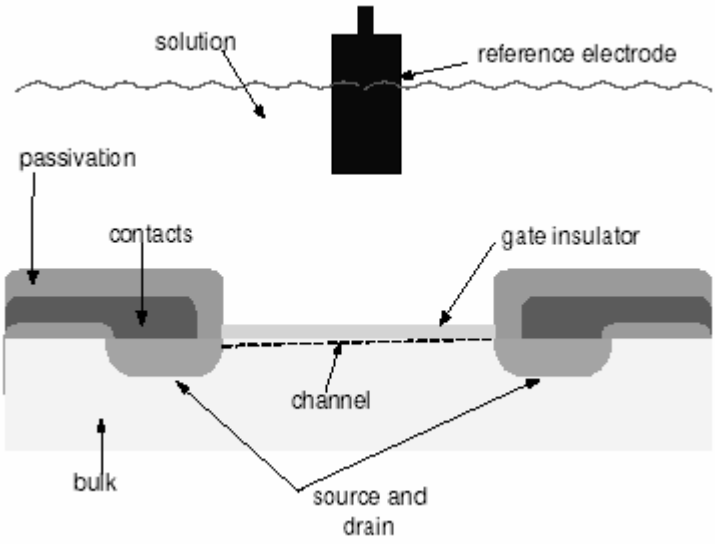

Figure 1. Cross-section of an ISFET structure. (Source: Janicki, M., Daniel, M., Napieralski, A.: *Parameter Extraction for Electro-chemical Simulations of Ion-Sensitive Transistors*. 10th International Conference Mixed Design of Integrated Circuits and Systems MIXDES 2003, Lodz, Poland, **2003**; pp. 450-455.)

The sensitivity of an ISFET is usually expressed as the gate-voltage change per decade of the hydrogen-ion concentration (pH), where the pH denotes -log $[H^+]$. For example, if the value of the pH is equal to 2, the concentration of the hydrogen ions amounts to be 10^{-2} mole per liter.

As measurement method, the ISFET is usually operated in the constant drain-current mode, which means that the change of the drain current due to the change of the ion concentration in the electrolyte is compensated by the modification of the reference-electrode potential (the gate voltage). The gate voltage is usually measured by using an analog-to-digital converter (ADC) [2,3,4].

This ordinary approach has several disadvantages. At first, to keep the drain current constant, additional electronics, whose inaccuracy can influence the resultant precision, is needed. Secondly, the hydrogen-ion concentration does not correspond directly to the gate voltage, only to a change of the gate voltage. In the third place, to represent the result in digital form, other ADC as separate electronic components are needed.

This contribution is devoted to a switched flip-flop-based preprocessing circuit for ISFETs. The principle of measurement consists in discontinuing the flip-flop value symmetry by the concentration

of hydrogen ions (pH) and its recovering by a balanced voltage of which the magnitude is set automatically by using a feedback circuit. Authors of reference [5] first used this idea in processing signals from chemical sensors. A switched flip-flop circuit with ISFETs is described in the following section.

Switched flip-flop with ISFETs

Fig. 2 shows a flip-flop with ISFETs. The circuit is controlled by an impulse generator and has two stable states, namely the states 'one' and 'zero'. Activating the flip-flop with a voltage impulse, the circuit switches to one from two stable states [6] and it depends on the asymmetry of the flip-flop which stable state it will be.

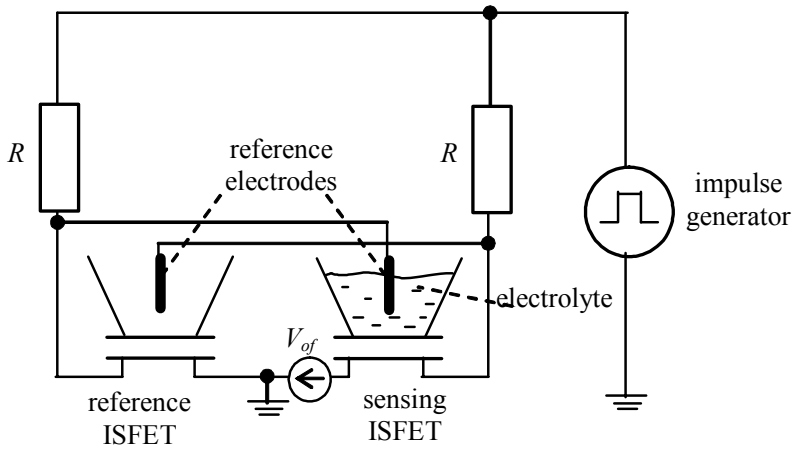

Figure 2. Flip-flop circuit with ISFETs.

Let us consider the asymmetry caused by mismatches in the reference and sensing ISFET. Since, however, only the threshold voltage of the sensing ISFET is influenced by the H^+-ion concentration of the electrolyte, an equivalent circuit diagram according to Fig. 3 can be drawn.

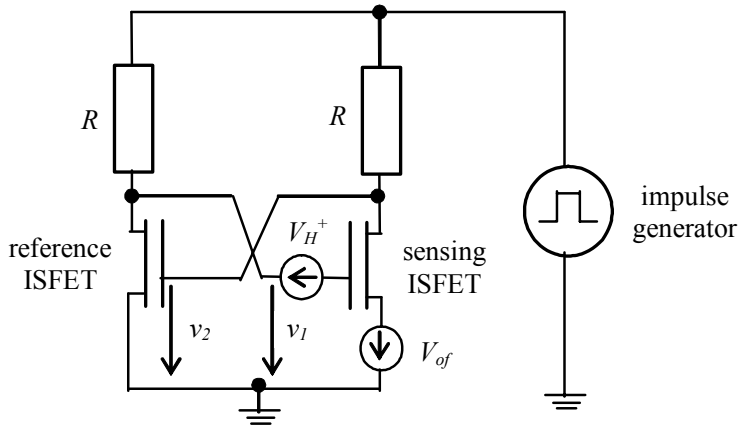

Figure 3. Equivalent circuit diagram.

Here, the voltage source V_{H^+} represents the change of the sensing ISFET-threshold voltage by the value $(R_gT/F).\log(H^+)$ [1], where R_g is the gas constant, T is the absolute temperature (K), F is the

Faraday constant and H^+ is the hydrogen-ion concentration. The principle of measurement is based on compensating this asymmetry by the balanced voltage V_{of}. Compensating the flip-flop asymmetry we can achieve $v_1=v_2$ [7]. Therefore, in a balanced state $V_{of}=-(R_gT/F).\log(H^+)$. Then, when thermal and shot noise mean values being zero [3], the probability of an 'one' and a 'zero' will be 0.5. This is known as the 50% state of a switched flip-flop [7].

The symmetry of a real flip-flop can be discontinued by other disturbances such as the influence of flicker noise, mismatches in resistors, output characteristics of ISFETs, etc. As shown in [8], the measured voltage V_{of} is given by the formula

$$V_{of} = -\frac{R_g T}{F}\log\left(H^+\right) + V_{offset} \tag{1}$$

where V_{offset} is the voltage needed to compensate the above disturbances. Thus, to eliminate the disturbances, two measurements must be performed, the measurement of V_{offset} when the influence of H^+ ions is absent and the measurement of V_{of} when the influence of H^+ ions is active. Then, a given chemical parameter can be calculated from equation (1). If, for example the, pH sensitivity is measured by using eq. (1)

$$pH = \frac{V_{of} - V_{offset}}{R_g T} F \tag{2}$$

where $pH=-\log(H^+)$.

Measurement set-up

As explained in the previous section, the voltage V_{of} reflects the hydrogen-ion concentration. To set the voltage automatically, a measurement set-up is chosen as depicted in Fig. 4.

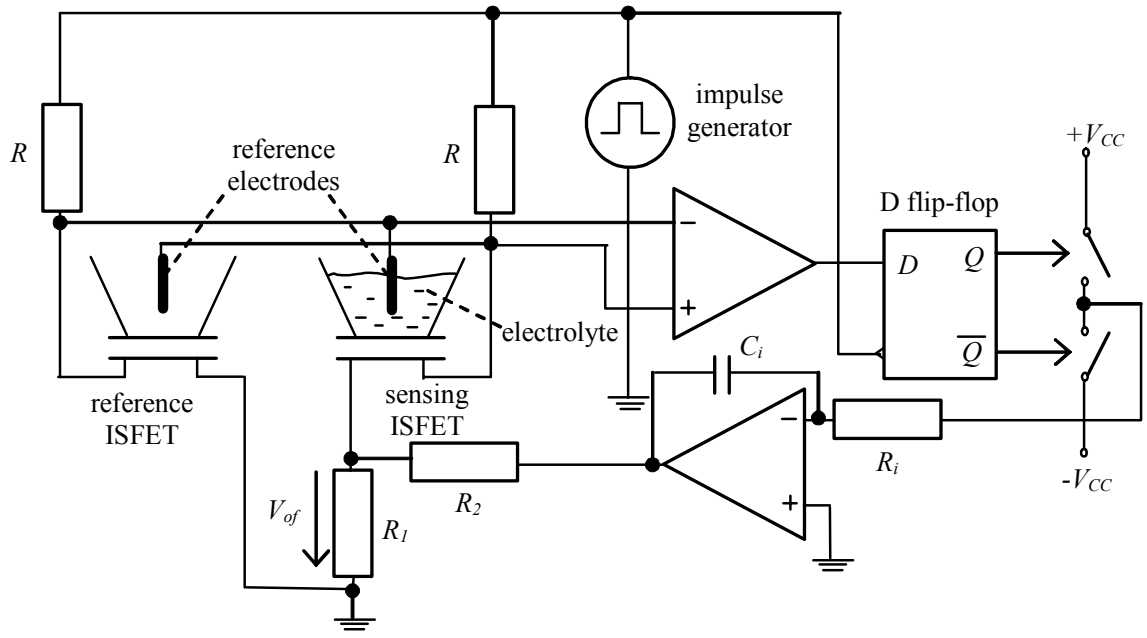

Figure 4. Measurement set-up.

As can be seen, the feedback circuit contains an input differential amplifier, a D flip-flop, an integrator and a resistive divider. A differential amplifier processes the series of 'ones' and 'zeros' from the flip-flop output. The actual logical state is sampled by the D flip-flop and depending on this state, one of two switches is turned on. Thus, the resistive divider voltage is being decreased or increased to balance the switched flip-flop. By processing the series of impulses from the output Q of the D flip-flop, the chemical parameter to be measured is represented in digital form.

The system depicted in Fig. 4 is a well-known Δ modulator [4] in which the switched flip-flop serves as a comparator and a sampling circuit. To quantify the magnitude of the voltage V_{of}, a digital integrator must be used (see Fig. 5). A reversible counter can be used in the simplest case. Then, the voltage V_{of} is given by the formula

$$V_{of} = N.\Delta \tag{3}$$

where N is the number of impulses read; the quantization step Δ is given by the extension

$$\Delta = \frac{V_{CC}}{R_i C_i} \frac{R_1}{\left(R_1 + R_2\right)} T_S \tag{4}$$

The uncertainty, obtained from the rectangular probability of distribution of measured pH sensitivity is given by formula

$$u_{pH} = \frac{2\Delta}{\sqrt{3}} \frac{F}{R_g T} \tag{5}$$

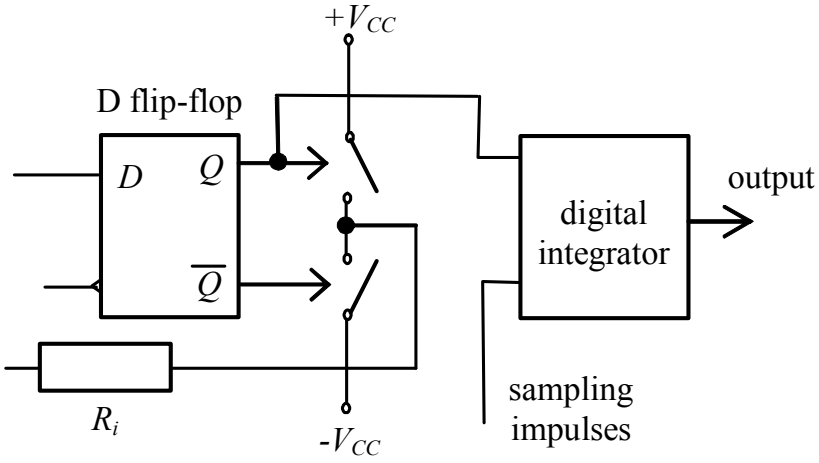

Figure 5. Processing the impulses by a digital integrator.

For the dynamical properties of the measurement system let us consider that

$$pH = pH_{\max} \sin\left(2\pi f.t\right) \tag{6}$$

Then, because of the maximal value of pH, the derivative of time t can be written as

$$2\pi f.pH_{\max} = \frac{\Delta}{T_S} \frac{F}{R_g T} \tag{7}$$

Here, the maximal measurable frequency *f* of pH is given by the formula

$$f = \frac{\Delta}{T_S}\frac{F}{R_g T}\frac{1}{2\pi pH_{\max}} \tag{8}$$

Results of simulation and discussion

The measurement system pictured in Fig. 4 was simulated in TSPICE. The approach which modifies the threshold voltage in dependence on the hydrogen ions in the existing SPICE MOSFET model was used for modelling the ISFET [1]. Thus, the H^+-ion concentration induces the change of the threshold voltage of the sensing ISFET by the value $(R_gT/F).\log(H^+)$. Other parameters of the used model are shown in Tab. 1.

Table 1. Parameters of ISFET SPICE model.

Parameter	Value	Unit
Low field carrier mobility μ_0	0.097	[m^2/Vs]
Maximal carrier velocity ν_{max}	1.10^5	[m/s]
Mobility modulation coefficient Θ	0.176	[V^{-1}]

The remaining parameters were set as follows: V_{CC} = 5 V, T_S = 3.34*10^{-5} s, R_i = 200 kΩ, C_i = 100 nF, R_1 = 200 Ω, R_2 = 10 Ω, R = 6.8 k Ω, and T = 294 ^{o}K. At first, the value of pH 4.7 was chosen. The corresponding integrator input voltage and V_{of} as functions of time are shown in Figs. 6 and 7.

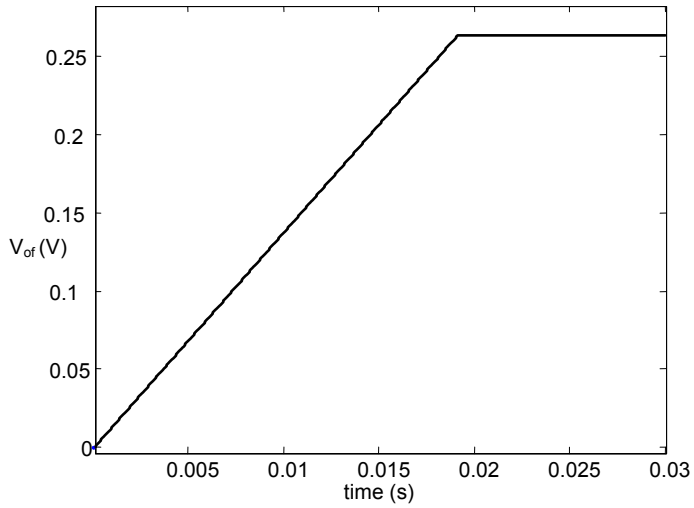

Figure 6. Output voltage of resistive divider as a function of time.

As shown in Fig. 6, the voltage V_{of} corresponding to pH 4.7 is obtained after 18 ms. At this moment, the positive impulses are generated only at the integrator input, whereas starting from this moment, the positive and negative impulses are generated statistically depending on the noise, as shown in Fig. 7. For t> 18 ms, the voltage V_{of} changes from 0.2631 to 0.26337. Then, using eq. (2) and

assuming V_{offset}= 0 and R_gT/F= 56 mV/pH it follows that the pH changes from 4.698 to 4.703. Hence, the maximal relative error is 0.064 % in this case.

The pH was then changed from 4.7 to 11. The corresponding relative error characteristics is shown in Figure 8. As can be seen, the maximal relative error is only 0.2%.

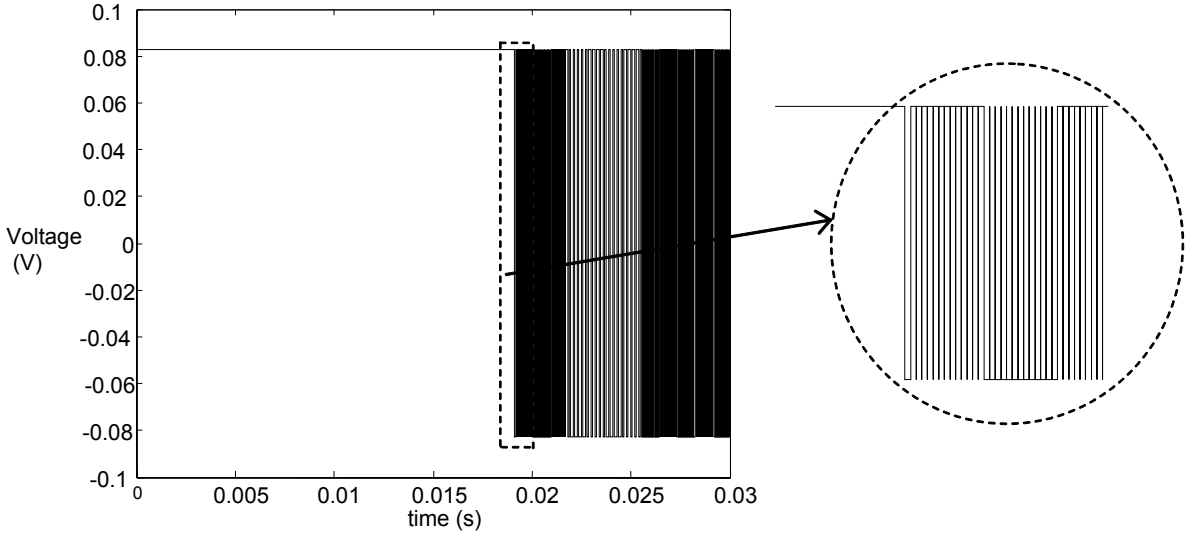

Figure 7. Sequence of impulses at the input of the integrator.

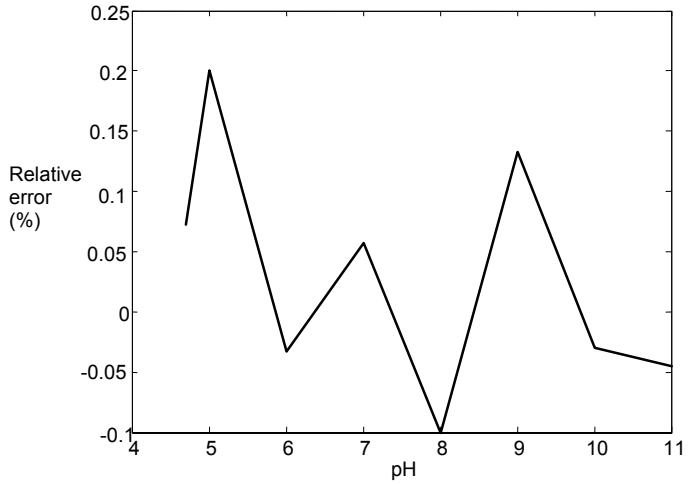

Figure 8. Relative error of measured pH.

Conclusions

A preprocessing circuit for signals from ISFET has been presented. The main part is a switched flip-flop with a reference ISFET and a sensing ISFET. The principle of measurement is based on changing the threshold voltage of the sensing ISFET through the concentration of hydrogen-ion changes, thus discontinuing the symmetry of a switched flip-flop. This asymmetry is compensated by a

voltage introduced to the flip-flop in such a way that the probability of 'one' equals to the probability of 'zero'.

Through the simulation with TSPICE, it was shown that the relative error of the measured pH is in the worst case 0.22%. Our further work will focus on the practical realization of this circuit.

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